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Reduction of AM-Induced Penalty in DPSK Receivers by Sum-Square Demodulation

T. N. Nielsen, U. Gliese, and K. E. Stubkjaer

Abstract—**A DPSK demodulator which is insensitive to the amplitude modulation induced by semiconductor optical amplifier phase modulators is proposed. The demodulator consist of *only* two additional power dividers/combiners compared to a traditional DPSK demodulator. Analysis show that the receiver penalty caused by amplitude modulation can be reduced from 2-4 dB to zero. The demodulator is finally demonstrated in a 2.5 Gb/s DPSK system experiment using an optical amplifier as phase modulator.**

INTRODUCTION

SEMICONDUCTOR optical amplifiers (SOA's) can be used as phase modulators in optical communication systems [1]-[3]. Compared to traditional phase modulators (e.g., $LiNbO_3$ phase modulators) the SOA has the advantages of gain and fairly low modulation power requirements. In addition, it lends itself readily to monolithic optoelectronic integration.

A problem of using SOA's as phase modulators is the amplitude modulation (AM) associated with the phase modulation (PM). The unwanted AM can be reduced by choosing an operating wavelength well above the peak gain wavelength [2], [4]. However, for operation at the peak gain wavelength, which is preferable due to the possibility for high net gain, the AM index for both bulk and MQW SOA's will be higher than 10%.

Here we show that the receiver penalty induced by the AM can be reduced to zero in DPSK systems with an appropriate demodulator. The demodulation scheme is demonstrated in a 2.5 Gb/s DPSK system experiment.

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CONVENTIONAL DPSK DEMODULATION

Conventional DPSK demodulation is performed by delay line discriminators as used in heterodyne coherent systems (c.f. Fig. 1). The bandpass filtered IF signal corresponding to one transmitted bit is given by

$$i_{\mathrm{IF}} = I_o(1 + m_t) \cdot \cos(\omega_{\mathrm{IF}} t + \phi_t) \tag{1}$$

where ω_{IF} is the intermediate frequency and m_t describes the amplitude variation of the IF signal caused by the SOA. The PM is described by ϕ_t which takes the values $\pm\pi/2$ in a DPSK system, and I_o describes the optoelectric conversion factor.

The AM generated in SOA's is governed by the linewidth enhancement factor α, giving the ratio between the PM and AM [5]; i.e., $m_t = \phi_t/\alpha$. The AM and PM generated by the SOA are both caused by modulation of the carrier density so m_t and ϕ_t are correlated.

In a conventional DPSK demodulator, a mixer squares the IF signal with the IF signal delayed by one bitperiod τ, and the PM-AM converted baseband signal is given by

$$V_b = V_o \cdot (1 + m_{t-\tau})(1 + m_t) \cdot \cos(\omega_{\mathrm{IF}}\tau + \Delta\phi) \tag{2}$$

where subscript τ denotes the delayed bit and V_o is a constant. $\Delta\phi = |\phi_t - \phi_{t-\tau}|$ is the phase difference between two succeeding bits and is either 0 (logic "space") or π (logic "mark"). The term $\cos(\omega_{\mathrm{IF}}\tau)$ can take the value -1 or $+1$ depending on whether the logic "space" is repre-

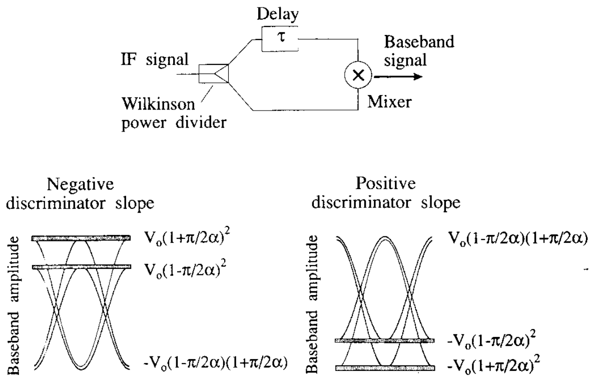

Fig. 1. Traditional DPSK demodulator and corresponding eye diagrams.

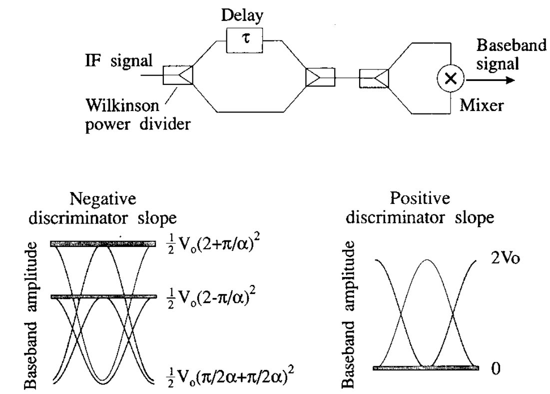

Fig. 2. Sum-square DPSK demodulator and corresponding eye diagrams.

sented at the bottom or the top point of the discriminator curve, respectively.

The logic space, i.e., $\Delta\phi = 0$, corresponds to the situation where $\phi_t = \phi_{t-\tau} = \pm\pi/2$. The associated value for m_t and $m_{t-\tau}$ is $\pm\pi/2/\alpha$ due to the correlation between PM and AM. The baseband amplitude corresponding to a "space" can therefore take the values $V_o(1 \pm \pi/2/\alpha)^2$, whereas the baseband amplitude for the logic "mark" only takes the value $V_o(1 + \pi/2/\alpha)(1 - \pi/2/\alpha)$. Because of the two "space" levels the resulting eye diagram will consist of two overlaid eye diagrams as shown in Fig. 1. Penalty is introduced due to the reduced baseband amplitude since the optimum decision level is placed between the "mark" and the lowest "space" level. From (2) it is furthermore seen that this baseband signal will appear independently of the chosen discriminator slope; i.e., cos $(\omega_{\mathrm{IF}}\tau)$ equal to -1 or $+1$.

Sum-Square DPSK Demodulation

In order to avoid the penalty caused by the AM, we propose a sum-square DPSK demodulator as shown in Fig. 2. Here the baseband signal is generated by adding the delayed IF signal to the IF signal itself and subsequently squaring the added signals in a mixer. The sum-square demodulator performs both a PM-AM conversion and an AM-AM conversion. The demodulated baseband signal is therefore given by

$$V_b = V_o \cdot \Big[\tfrac{1}{2}(1 + m_t)^2 + \tfrac{1}{2}(1 + m_{t-\tau})^2 + (1 + m_t)(1 + m_{t-\tau})\cos(\omega_{\mathrm{IF}}\tau + \Delta\phi)\Big]. \quad (3)$$

The baseband level for the logic "space" consist in this case of a contribution from the AM-AM conversion (two first terms) and a contribution from the PM-AM conversion (last term).

For the positive discriminator slope (cos $(\omega_{\mathrm{IF}}\tau) = -1$) the two contributions adds 180° out of phase and the "space" level will only take the value 0 independent of the AM. So, for the positive discriminator slope only one eye diagram will appear, and the penalty induced by the amplitude variation is zero. It should be emphasized that this property is only valid because the phase and amplitude modulation generated by the SOA are correlated. For the negative discriminator slope (cos $(\omega_{\mathrm{IF}}\tau) = +1$) the two contributions add in phase and the AM-induced receiver penalty is even more severe than for the traditional DPSK demodulator.

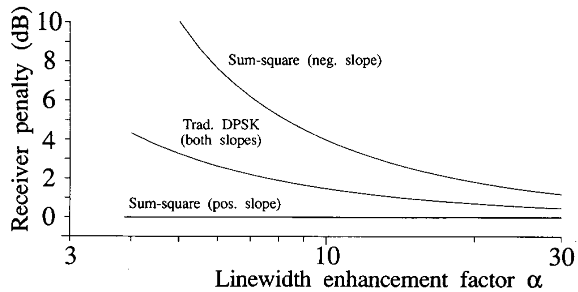

Fig. 3. Calculated AM-induced receiver penalty.

The results are clarified in Fig. 3 where the calculated AM-induced receiver penalty in a DPSK system is shown as a function of the linewidth enhancement factor α for both the conventional DPSK demodulator and the sum-square demodulator. The calculations are based on the SNR and the AM-induced reduction of baseband amplitude. It should notice that equal baseband amplitudes will be generated by both schemes if no AM is present. It should be emphasized that zero receiver penalty is obtained independent of bit rate since the phase of the AM relative to the PM has no influence in this scheme.

It should also be noticed that demodulation on the positive discriminator slope can be assured without adding any system complexity. In a DPSK system the IF is restricted to a multiple of half the bit rate. Half of these IF values correspond to the positive discriminator slope and the other half to the negative. The only system constraint using the sum-square demodulation scheme is thus a reduction of the possible IF values by a factor of 2.

Results

The sum-square demodulation scheme is demonstrated in a 2.5 Gb/s DPSK system experiment consisting of an optical delay line demodulator followed by a direct detection receiver [2]. This demodulation scheme is equivalent with the electrical sum-square scheme since the photodiode is a sum-

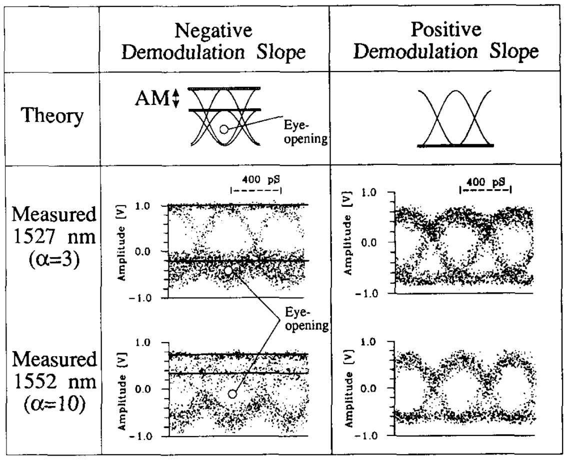

Fig. 4. Measured eye diagrams.

square detector. Light from a DFB laser is coupled into the SOA and the injection current is modulated with a 2.5 Gb/s NRZ data signal. Furthermore, an equalizer is added in order to extend the bandwidth capability of the SOA [2], [3]. For the experiments, an optical input power level of −7 dBm is used and the fiber-to-fiber gain is 10 dB, resulting in an optical output power of +3 dBm.

Fig. 4 shows the measured eye diagrams obtained by demodulation on the two different slopes of the discriminator curve. Two transmitter lasers with different wavelengths are used to demonstrate the results for different AM-indexes. The AM-indexes due to the phase modulator are 15% ($\alpha = 10$) and 50% ($\alpha = 3$) for 1552 and 1527 nm wavelength, respectively.

For demodulation on the negative slope, a two-level eye diagram appears, whereas only one eye diagram appears for demodulation on the positive slope. It is furthermore seen that this result is independent of the amount of AM, and receiver penalty is consequently reduced to zero using the sum-square demodulation scheme.

Conclusion

We have proposed a sum-square DPSK demodulator which is insensitive to the amplitude modulation induced by SOA's used as phase modulators. Furthermore, a thorough analysis is presented for the eye diagrams that result from the conventional as well as the sum-square DPSK demodulator. Compared to the conventional DPSK demodulator, the sum-square demodulator *only* consists of two additional simple dividers/combiners, and the only system constraint to assure demodulation on the positive slope is a halving of the possible IF's.

In order to demonstrate the behavior of the demodulator, we have performed a 2.5 Gb/s system experiment using an optical delay line demodulation that has the same property as the proposed electrical sum-square demodulation. The measurements show, in agreement with theory, that the proposed demodulation scheme is an attractive solution for reduction of the AM-induced receiver penalty. Semiconductor optical amplifiers operated at the peak gain wavelength can therefore, with great advantage, be used as phase modulators in DPSK systems in spite of the inevitable AM.

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